

The University of Genoa smart polygeneration microgrid test-bed facility: The overall system, the technologies and the research challenges

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ABSTRACT

Nowadays, as set by the EU 20-20-20 targets, the reduction of primary energy use and greenhouse gas emissions in the energy sector can be attained by increasing the use of renewable sources and improving energy efficiency. Many national and international research programs are aiming at developing innovative technologies and new energy management strategies in order to reach the targets set out in the 20-20-20 directive.

In this context, a primary role is played by the Distributed Generation (DG), which refers to the electrical and thermal generation located near to the place of use, exploiting available renewable sources. One of the best way to exploit the emerging potential of DG is to take a system approach which views generation and associated loads as a whole concept called “microgrid.” The sources can operate in parallel to the grid or can operate in island, providing utility power station services. Utilization of waste heat from the sources will increase total efficiency, making the polygeneration microgrid more financially attractive and “smart” from the energy consumption standpoint. The “smartness” is also in the management system, where control strategies aiming at the optimization of technical, economical and environmental issues are typically implemented.

This paper deals with smart microgrids, addressing basically the following topics: (1) to review methods, models, tools, technologies and research challenges in the specific field; (2) to present the University of Genoa Smart Polygeneration Microgrid (SPM), built with the financial contribution of the Italian Ministry of Education, University and Research at the decentralized Savona Campus facilities. The SPM produces energy at low emissions for the University and operates as a test-bed facility for research, testing and development of smart grid components.

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1. Introduction

The “smart grid” concept involves different issues related to the “sustainable energy” framework, such as integration of renewable sources into the power delivery system, distributed generation and storage, use of plug-in electric vehicles, dynamic systems control, data management, utility communication and advance metering. Different definitions of smart grid are available in the literature. For example, Berry et al. [1] describe a smart grid as a collective of geographically proximate electrically connected loads and generators, while the European Technology Platform for Smart Grids (established in 2006 by the European Commission) defines it as “an electricity network that can intelligently integrate the actions of all users connected to it—generators, consumers and those that do both—in order to efficiently deliver sustainable, economic and secure electricity supplies”.

As reported by Higgins et al. [2], smart grid technology supports a wide range of applications in power systems, such as protection and automation of the distribution system and security. Asano et al. [3] highlight that the smart grid concept has been developed and implemented intensively worldwide, with significant research activities in US, EU, Japan and Canada; in particular, it is important to cite the Microgrid Laboratory Test Bed, realized in Ohio by the Consortium for Electric Reliability Technology Solutions (CERTS), described in [4].

A microgrid can be seen as an aggregation of distributed energy resources (DER) of small size (such as photovoltaics, wind generation, fuel cells, cogeneration units—CHP, concentrated solar power—CSP, mini-hydro, energy storage), able to efficiently and environmentally friendly supply end-users according to power production control strategies and advanced demand response (DR) policies, set by an intelligent Energy Management System. Typically, the microgrid can be operated in two configurations: grid-connected or islanded.

As assessed by Asano et al. [3] and Jenkins et al. [5], the increasing interest on microgrids is due to their many potential benefits, namely to provide reliable, secure, efficient, and sustainable electricity.

Microgrid research fits very well with ongoing smart grid activities through the world and several issues need to be investigated [6].

Experimental tests and demonstration projects are very useful to derive new methods and tools for the optimal management of smart grids. Specifically, they allow studying, analyzing and validating in an effective way the mix of technologies for sustainable energy production, centralized and decentralized control and communication architectures, optimization of the overall system, monitoring, reliability and robustness of different operating conditions.

Basu et al. [7] state that microgrids represent an emerging challenge in the energy sector, though still not matured currently. Thus, extensive research and pilot projects need to be undertaken in order to increase microgrids competitiveness in the deregulated electricity market. As assessed by Suryanarayanan and Mitra [8], several technologies have to consolidate in order to make smart grids a reality; the interconnection of distributed energy resources (DER) is a challenge, considering safety, control and protection issues associated with bi-directional electricity flows.

The aim of the present work is twofold: to describe methods, models, tools, technologies and open problems related to smart microgrids, and to provide a description of the Smart Polygeneration Microgrid (SPM) of the Genoa University located at Savona Campus teaching & research facilities, with specific attention to future research challenges.

The SPM includes a number of heterogeneous distributed energy sources, such as gas microturbines, wind turbines (horizontal and vertical axis), photovoltaic and concentrating solar power (CSP), integrated with storage devices (such as sodium–nickel batteries and power capacitors) on a low voltage distribution system. The SPM has two main objectives: to produce clean energy for the University loads and to operate as a test-bed for research, testing and development of management strategies and also power components. In particular, the system has been designed to allow the following activities:

- Implementation and validation of algorithms to predict the production from the renewable sources (wind, solar), with the help of sun radiation and wind forecasting tools.
- Implementation and validation of methods for the optimal operation of storage systems and of dispatchable sources (gas turbine), on the basis of the information on renewable production gathered by the algorithms at the previous item, in order to make the system follow a day-ahead production schedule.
- Power flow control at the interface with the external grid, in order to control the exchange of active and reactive power.
- Storage of energy measurements at each renewable generation in a centralized database, in order to check the actual correlation with the energy forecast over a long period of time and to make available an extensive prediction/measures data set for further researches.
- Testing of new “smart” power converters for improving the integration of renewable sources into the power delivery system.

The paper is organized as follows. Firstly, in Section 2 several smart grid projects around the world are cited while in Section 3 a brief survey on research activities carried out at Savona Campus facilities is reported together with a detailed description of the

SPM overall structure. Next, in Section 4, the SPM technologies are examined and the relative research challenges are outlined. Then, the different subsystems (electrical, thermal, control and communication) of the microgrid are analyzed, respectively, in Sections 5–7 in the context of state of the art literature. Finally, in Section 8, some conclusive remarks are drawn.

2. An overview of the smart grid projects around the world

Nowadays, many national and international projects are focused on the distributed generation and smart grid concept. It is important to cite the EPRI Smart Grid Demonstration Initiative [9], which is an international collaborative initiative to demonstrate the integration of Distributed Energy Resources (DER) in large scale demonstration projects. The four main goals of the aforementioned initiative are: study of the analytic methods and tools, integration technologies and systems development, host-site demonstration selection and research, technology and knowledge transfer. In the following, the most important smart grid projects around the world are briefly described.

2.1. Smart grid projects in the world

In USA many research projects are focused on the development of microgrids for peak load reduction; among them, it is worthwhile to mention the CERTS Microgrid Demonstration project, which is a full-scale test-bed installed near Columbus, Ohio, and operated by American Electric Power [4,10]. The test-bed has three feeders: the first feeder has two 60 kW converter based sources driven by natural gas; the second feeder has a single source of same type and capacity, while the third feeder is connected to the utility but it could be powered by the DERs when static switch is closed without injecting power to the utility. Each generator set is provided with battery energy storage at its DC bus. A central communication system based on Ethernet is used to connect the Energy Management System (EMS) and the generator sets to dispatch DER set points; the microgrid can be operated both grid-connected and in island.

The CERTS project belongs to the Renewable and Distributed Systems Integration (RDSI) Program [11], managed by the U.S. Department of Energy, which aims to alleviate congestion, reduce greenhouse gas emissions, and improve reliability by investigating issues such as microgrid technologies, distributed generation, two-way communication systems and demand response programs. RDSI is sponsoring nine demonstration projects in order to develop new approaches to generating energy by harnessing the power of cutting-edge technologies as diverse as photovoltaics, fuel cells, hydro turbines and pumped water storage. These nine projects are located throughout the United States and they are based on the integration of plug-in hybrid vehicles (PHEVs), wind turbines, photovoltaics, pumped storage, compressed air storage, microgrid technologies, and feeder automation systems.

Among these projects, it is interesting to cite the following:

- The Never-Failing Perfect Power Prototype, developed by the Illinois Institute of Technology, which incorporates smart microgrids and control technology, distributed generation, combined heat and power, and renewables [12].
- The Fort Collins Demonstration Project which is focused on the research, development, and demonstration of a coordinated and integrated system of 3.5 MW of mixed distributed resources in Fort Collins, Colorado to achieve a 20–30% peak load reduction on two distribution feeders [13].
- The West Virginia Supercircuit Project, operated by Allegheny Power, based on both different technologies such as biodiesel combustion engine, photovoltaics, energy storage and on

advanced wireless communication and dynamic feeder reconfiguration [13].

As described in [9], the Exelon project developed by the Philadelphia Electric Company and the Drexel University, aims to deploy a distributed energy management system which could demonstrate the benefits connected to the integration of DERs in a smart campus microgrid; in [9] the PNM Resources and the Southern California Edison Smart Grid Demonstration Projects are described too.

Regarding islanding and microgrid experience, Lidula and Rajapakse in [14] describe many experimental microgrids and microgrid test-bed facilities in the USA and Canada, among which we can mention

- The Boston Bar-BC Hydro system which is a microgrid that is interconnected to a 69 kV feeder, through a 69 kV/25 kV substation comprising of three radial feeders, and is composed of two 4.32 MVA run-of-river hydro power generators, without storage units.
- The UW microgrid test-bed at the University of Wisconsin, implemented to investigate the modeling and control issues in integrating diesel generators into microgrids.
- The Aichi microgrid project in Japan that concerns on a power supply system composed of molten carbonate and solid oxide fuel cells, photovoltaics and sodium–sulfur batteries.
- The Kyotango project, in Japan, which consists in a virtual microgrid because each DER and demand site is connected to a substation of the utility grid and they are only integrated by the control system. In the grid three gas engines, several PV systems and a small wind farm are installed.
- The Sendai microgrid, in Japan, which comprises two gas engines, one fuel cell, photovoltaics and battery energy storage systems.

Furthermore, some interesting projects are going to be developed in other countries such as India and China, as reported by Lidula and Rajapakse in [14]. The Teri smart mini-grid in India, as described in [15], is based on the use of different distributed generation technologies, such as solar PV, wind generator, biomass gasifier and diesel engine. Several microgrid projects are been developed in Australia: as reported in [16], it is notable to cite the CSIRO project in Newcastle, New South Wales, and many other projects developed in Western Australia, almost all based on wind and solar energy. About the development of smart grids in Africa, it is important to say that at the Smart Grid Workshop on 12 April 2012 in California it has been decided to establish an electricity industry smart grid institute to be known as the South African Smart Grid Initiative (SASGI) [17].

2.2. Smart grid projects in Europe

In European countries, many research and development projects, benefitting from national or European funding, are focused on smart grids, energy efficiency, renewable sources and distributed generation. About smart grids, the list of the main current projects is reported in [18]; in particular, the projects are classified in the following categories: Grid Automation–Transmission, Grid Automation–Distribution, Specific Storage Technology Distribution, Integrated System, Smart Meter and Advanced Metering Infrastructure (AMI), Home Application–Customer Behavior.

Many projects concern on the installation of innovative smart meters and AMI systems. In Portugal, the EDP Distribuição Company is developing the INOVRID project which aims at replacing the current LV meters with electronic devices integrated

in a smart grid, in order to gather information and provide new services to consumers. A similar project is worked out by the Iberdrola Distribucion Company in Spain (GAD project) and by ERDF in France (Pilot Linky). In Belgium, the Ores company is installing 1500 electricity and gas smart meters in the cities of Nivelles and Marche-en-Famenne, while the Danish Energy Industries Federation manages a demonstration project on demand response, to which more than 500 households participate; the Center for Electric Power and Energy of the Technical University of Denmark aims to develop innovative communication systems for smart grids, based on the new international IEC61850-family of open standards.

In the Grid Automation–Transmission category, the Red Eléctrica de España S.A. uses the standard IEC61850 as a mean to improve the design, maintenance and operation of the substation automation systems, whilst the Energinet.DK in Denmark develops systems that can monitor the overall power system state to prevent critical situations.

Regarding the Grid Automation–Distribution Category, it is interesting to report that the Belgian Ores company is studying the impact of electrical vehicles slow and fast charging on smart grids. In the Netherlands, the KEMA Company is setting up 5–10 large-scale smart grid demonstration projects with a total of around 5000 private and small business end-users. In the same project category, the AIT Austria company is developing the “DG DemoNet-Smart LV Grid” project on smart planning, monitoring and control approaches for the integration of distributed energy sources and flexible loads in load voltage networks.

Regarding the storage technologies, both the Technical University of Denmark and the RWE Power AG in Germany are evaluating opportunities to use compressed energy storage systems, while the Red Eléctrica de España S.A. is testing a electrochemical battery in a substation of the transmission grid.

In the Home Application category, the Irish ESB Networks company is leading a project that examines in detail, through modeling and demonstration, the impact of electric vehicles on two typical LV circuits, while in Austria the Salzburg AG is investigating how to reduce energy consumptions in smart grids.

Most of the projects classified as Integrated System are being deployed in Denmark. In particular, the Energinet.DK Company aims to build and demonstrate a complete prototype (EcoGrid EU project) of a system characterized by more than 50% energy production from renewable sources; the same company is developing a project to control 300 smart heat pumps as if they were a unique energy storage facility. The PV-Island Bornholm project in Denmark aims at installing photovoltaics (5 MW) on the island of Bornholm, in order to test how this technology, based on a fluctuating energy source, could be implemented in a future intelligent power system. In Germany, the RWE DAG is developing a concept of virtual power plant, while in Austria the Salzburg AG is constructing a demonstration building in order to evaluate advantages and disadvantages of smart grids in connection with buildings.

Other important demonstration projects in Europe are

- The PREMIO project developed by Electricité de France (EDF) in the PACA region to integrate distributed generation units, storage systems, renewable energy resources and loads.
- The Bronsbergen Holiday Park microgrid in The Netherlands where there are 108 cottages with PV modules characterized by a peak generation capacity of 315 kW; the microgrid is connected to a 10 kV medium voltage grid and is equipped by a central energy storage system.
- The residential microgrid of Am Steinweg in Stutensee, Germany, where the main energy sources are: a 28 kW_e CHP unit, different PV installation (35 kW) and a lead-free battery

bank with a bi-directional inverter; about 100 apartments are linked to the grid.

Regarding the smart grid development in Italy, it is important to cite the CESI Ricerca DER test-bed which is a low voltage microgrid (400 V), connected to the medium voltage grid (23 kV) by means of a 800 kVA transformer and a suitable converter, and constituted by several DERs and controllable loads [14]. Then, there is a smart grid project in the La Sapienza University in Rome, where internal combustion engines, photovoltaics, fuel cells, micro gas turbines and absorption chillers are installed in order to produce electricity and thermal energy for the University departments. Furthermore, many Italian companies are concerned on the smart grid issue. For example, Enel SpA has been building a smart grid pilot project in Molise region, with the aim of installing monitoring systems and sensors, lithium-ion batteries, electric vehicle recharging stations, and innovative equipments to monitor electricity consumptions of residential buildings.

3. The Savona University Campus and the Smart Polygeneration Microgrid (SPM)

The Savona University Campus is a decentralized research and teaching facility of the University of Genoa [19,20]. It is spread over an area of approximately 50,000 m² and hosts some courses from the Faculties of Engineering (tailored to the environment and energy sectors), Economics, Medicine and Surgery, and Media Sciences, with more than 1700 students. In the Campus, there are also a canteen, a café, a library, some residence halls, a tennis court, a football field, a gym and some green areas. The Engineering Faculty laboratories are active in the fields of renewable energy systems, greenhouse gas emissions, carbon capture and storage technologies, energy efficiency, combustion processes, thermoelectric power plants, electricity smart grids, dynamic simulation, utilities markets and decision support systems.

3.1. The Campus activities and facilities in the energy sector

Currently, at Savona Campus facilities, two 400 kW_{th} boilers fed by natural gas and a 28 kW_e cogeneration gas turbine are installed to satisfy the Campus thermal energy consumption. All the buildings have a centralized air conditioning system and energy labs located in hangars are neither conditioned nor heated. Residence halls have all services supplied by electricity. In 2006, a research project has been developed by Bracco et al. [21] in order to install a distributed generation system composed by a set of micro-cogeneration gas turbines (to be located near the thermal power station and to supply energy to both the Campus, the municipal swimming pool and some nearby firms) and photovoltaic modules (to be installed on the roofs of the academic buildings).

In addition, in the energy labs of the Savona University Campus the following machines are used mainly for teaching and research purposes: a hydrogen electrolyzer characterized by a 0.5 Nm³/h hydrogen flow rate; a 12 kW_e biomass downdraft gasifier coupled with a reciprocating internal combustion engine; a 100 kW_e micro gas turbine test grid; a 250 kW_e turbocharged Diesel engine.

3.2. The Smart Polygeneration Microgrid (SPM)

The project SPM begun in 2010 as a joint “special project in the energy sector” between the University of Genoa and the Italian Ministry of Education, University and Research, which is the public body financing the initiative [19,20]. During the year

2011 the preliminary design, the final design and the working plan of the infrastructure have been developed and in the current year 2012 works will start. The expected date for the test-bed completion is June 2013. The project SPM is aimed at creating an R&D facility based on the use of both renewable and fossil sources to produce thermal and electrical energy in accordance to a distributed generation strategy. The SPM will permit to optimize the thermal and electrical energy consumptions of the Campus, minimizing the CO₂ emissions, the annual operating costs and the primary energy use [19,20]. As a consequence, the SPM will determine both economical and environmental benefits; in the future, it will be possible to finance research activities by means of the savings derived from the SPM management with respect to the Campus existing situation.

The microgrid will consist of several renewable and traditional generating units integrated with storage devices and connected by a electrical grid. The overall system will be monitored from a control room where the signals coming in real time from field sensors will be stored and analyzed in order to regulate all the equipment and devices and to determine optimal management strategies.

Due to its modular structure, the SPM could be further developed in the future by the installation of new energy state-of-the-art-technology production plants. Furthermore, the SPM will be also a useful tool to connect academic research with private industrial companies and network operators (gas and electricity), in order to develop joint scientific program based on the demonstrator use.

The University of Genoa aims at developing different research activities on the SPM, such as

- Implementation and validation of algorithms to predict the production from renewable sources (wind, solar), on the basis of solar radiation and wind forecasting tools.
- Implementation and validation of methods for the optimal dispatch of non-renewable source (gas turbine) and for the charge/discharge of storage systems, on the basis of the information made available from the forecasting algorithms and taking into account constraints such as charge/discharge rate limitations of batteries, in order to make the system follow a day-ahead production schedule.
- Adoption of power flow control at the interface with the external grid, in order to regulate the exchange of active and reactive power with the same grid.
- Storage of the energy measurements of each generation unit in a centralized database, in order to check the actual correlation with the energy forecast over a long time period and to make available an extensive data set for further researches.
- Development of methods and control strategies for single and multi generation systems in order to enable the transition from “grid-connected” mode to “island” one.
- Monitoring and alarms management.
- Condition monitoring of smart grid components.

4. SPM technologies

The SPM is basically composed of (see Figs. 1 and 2)

- A micro-cogeneration gas turbine fed by natural gas.
- A cogeneration internal combustion engine fed by biofuel.
- A photovoltaic field.
- two solar-powered Stirling engines.
- Two micro-wind mills.
- Two electrical vehicle recharge stations.
- Electrical battery storage.

- Thermal storage devices.
- Absorption chillers.

All the SPM components will be equipped with a communication system compliant with the industrial protocol IEC 61850, which allows the remote control of each device, data acquisition from all sensors and guarantees the interoperability among equipment from different suppliers. IEC 61850 can contribute also to wiring and installation time reduction.

4.1. The PV unit

The photovoltaic modules (PV) will be installed on the roof of one building, covering an area of about 400 m², as indicated in Fig. 2. The plant is characterized by the main data reported in Table 1.

The monitored data will be: meteorological data (solar irradiance on module plane, ambient temperature and pressure, module operating temperature) and electrical data of each array (current and voltage). The PV system will be connected to the smart microgrid through a dc/ac power converter that allows for remote control of active and reactive power.

4.2. The micro CHP gas turbine

A consistent amount of the thermal and electrical consumptions of the Campus will be covered by the energy produced by the Capstone C65 CHP (Combined Heat and Power) gas turbine fed by natural gas. The gas turbine is characterized by the performance data reported by Table 2 (at 15 °C ambient temperature and at sea level, considering 60% relative humidity).

The C65 gas turbine is characterized by compact size, low weight, reduced noise and low maintenance requirements. The electrical energy produced by the machine is used to partially satisfy the electrical load of the Campus. The gas turbine is also equipped with a by-pass in order to discharge the exhaust gas directly into the atmosphere. The gas turbine will be installed next to the C30 gas turbine already in operation in the Campus. The gas turbine control and data acquisition system will be connected to the SPM control room; in particular, the control system must be capable of receiving an external set-point of active and reactive power during operation in parallel to the public network and a set point of voltage and frequency during island mode.

4.3. The wind turbines

The SPM contains also two small wind turbines, although the Campus is not properly a windy location, due to its location at sea level surrounded by hills. The aim of such installations is to study the interaction between the wind turbines and the SPM: in particular, the research will be focused on the use of super-capacitors in order to smooth the wind power delivered to the grid. Specifically, a horizontal axis wind turbine (HAWT) and a vertical axis wind turbine (VAWT) will be installed; both machines are characterized by a rated power equal to 3 kW_e and a very low cut-in speed (2.5 m/s). In the proximity of the turbines, meteorological instrumentation will be placed in order to monitor the wind speed and direction, the ambient temperature, pressure and humidity, and the rainfall.

The VAWT has an internal rotor made of Savonius blades and an external rotor made of Darrieus blades and is equipped by a yaw positioner. The tower and the windmill are respectively 12 m and 3 m high. The machine will be exposed to prevailing wind, far from the student residence halls and neighborhood houses.

The HAWT is characterized by a diameter of 5 m and has three blades; the tower and the windmill are, respectively, 8 m and 1.6 m high. The machine will be installed in the proximity of energy labs, in the northern zone of the Campus (see Fig. 2).



Fig. 1. Location of the Savona University Campus.

4.4. The solar-powered Stirling engines

Two parabolic solar concentrator systems (CSP) will be installed in order to produce, by means of two Stirling free-piston engines, thermal and electrical energy. Each machine is characterized by an electrical power output of 1 kW_e and a thermal power output of 3 kW_{th}. Each solar concentrator is characterized by: surface of 10 m², diameter of 3.75 m, focal distance of 2.26 m; the unit is equipped by a biaxial solar tracking system. The machines have a yearly average efficiency of at least 53% (13% electrical efficiency and 40% thermal efficiency).

Table 1
The PV installation data.

Rated power	49.9	V
Estimated annual energy production	58.0	MWh _{el}
Tilt angle	30	deg
Azimuth angle	−30	deg
Module efficiency	14.5	%
Open circuit voltage	37.92	V
Short circuit current	8.63	A
Cell voltage at which power is maximum	27.73	V
Cell current at which power is maximum	8.08	A

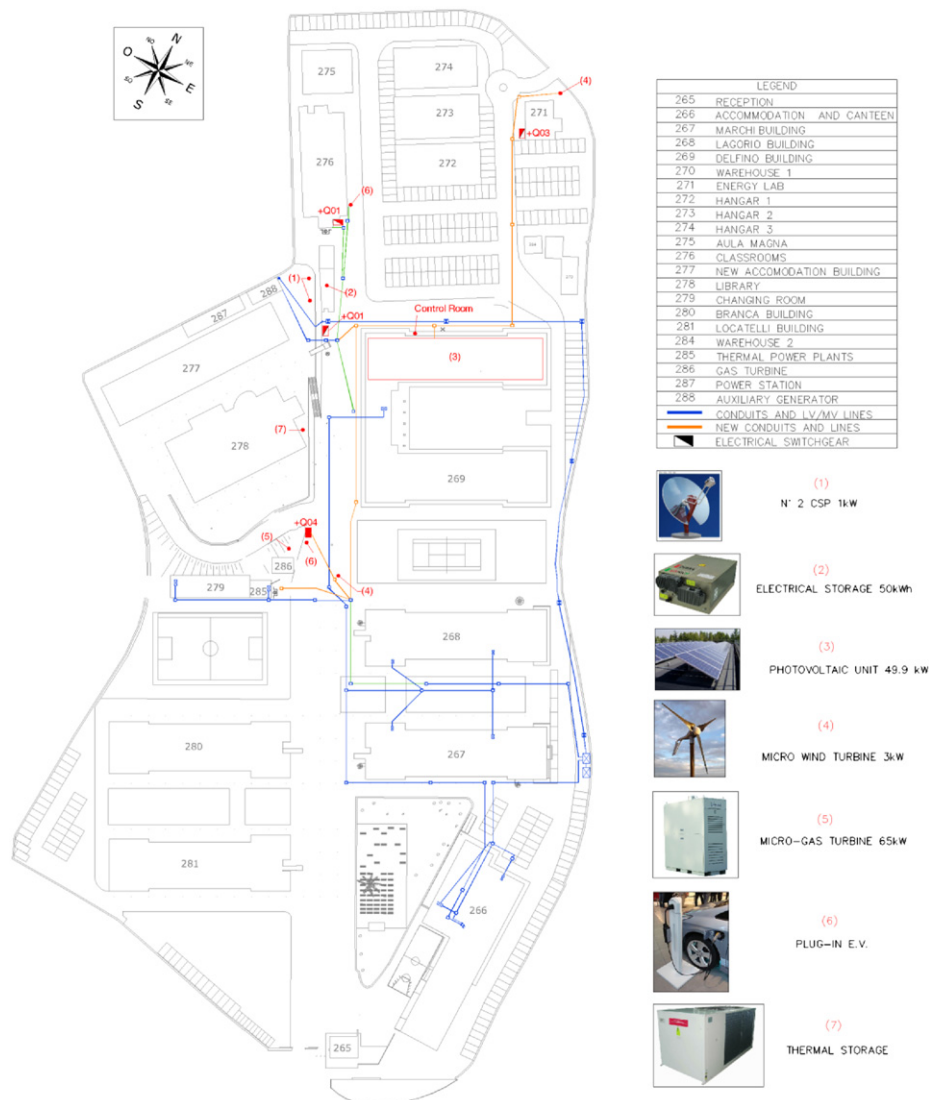


Fig. 2. Layout of the SPM.

Table 2
The micro CHP gas turbine data.

Rated electrical power	65	kW _e
Rated thermal power	112	kW _{th}
Fuel consumption	23	m ³ /h
Exhaust gas mass flow rate	0.49	kg/s
Overall efficiency higher than	85	%
Electrical efficiency	29	%
Exhaust gas exit temperature	309	°C

Table 3
Absorption chillers data.

Cooling capacity	32.5	kW _{th}
Coefficient of performance	0.75	–
Thermal power input	43.3	kW
Hot water inlet temperature	70/95	°C
Cooling water inlet temperature	25/40	°C
Chilled water minimum temperature	6	°C

The generated thermal energy will be used to produce warm water or, by absorption, for air conditioning purposes. When it is raining or hailing or the wind speed is higher than 50 km/h, the solar concentrator can close on itself protecting the whole system. The machine is equipped with digital transmission devices for remote control. Since the machine produces electrical energy in alternate current, it is not necessary to install any inverter.

4.5. The absorption chillers

Two absorption chillers will be employed in order to refrigerate the library during the summer. The heat input to the systems will be provided by the exhaust gas at the exit of the C65 gas turbine; by this way, it will be possible to use the cogeneration gas turbine also during the summer without discharging high temperature gas into the atmosphere. The two absorption chillers will be coupled with a cooling tower necessary to transfer the waste heat to the ambient.

Each absorption chiller is characterized by the main technical data reported in Table 3.

Furthermore, a tank having a capacity of 3000 l will be installed in order to store the chilled water; by this way, it will be possible to satisfy thermal power peaks of the library building without the intervention of the existing (and power consuming) air-conditioning heat pump.

4.6. The electrical storage

Storage systems are usually designed to balance energy production and load demand. They are capable to operate either as a load to absorb surplus energy or as a generator to meet peak load demand.

An electrical storage system based on high voltage Sodium–Nickel batteries will be installed to increase the SPM flexibility. In particular, the system has an energy storage capacity of about 100 kWh. These innovative batteries, called “SoNick”, are based on the molten salt sodium nickel chloride technology, an alternative to molten salt sodium sulfur (NaS) batteries. Like these latter, SoNick batteries are characterized by a molten sodium anode separated from the cathode by a tubular solid electrolyte made out of beta-alumina. The cathode is primarily composed of nickel chloride (NiCl₂) rather than of sulfur. During the discharge process, sodium ions are formed in the anode and migrate through the solid electrolyte into the cathode. The primarily chemical reaction in the cathode is the exchange of Cl between

NiCl₂ and the sodium ions resulting in the growth of large crystals of NaCl. During discharge, this process is reversed and the NaCl crystals decompose and the sodium ions migrate back into the anode.

The battery system will be monitored in real time and appropriate control strategies will be used for its optimal operation.

The main functions of the energy storage device are: to balance the power demand with generation, to reduce problems related to variability and intermittency of renewable sources, to mitigate instability of electrical systems, and to provide the initial energy required for the transition between grid-connected and island operation mode.

4.7. The electric vehicles charging stations

Two electric vehicles charging stations will be installed in the SPM, in accordance with the IEC/EN 61851-1 Standard; they will be used in the charge mode 3 (slow or fast charging using a specific EV multi-pin socket with control and protection functions). The vehicle will be connected directly to the station via specific socket and plug and a dedicated circuit. A control and protection function will be also installed, allowing load-shedding, so that electrical loads can be enabled or disabled during vehicle charging, and the optimization of the electric vehicle charging time. Recharging a large battery pack represents a high load on the electrical grid, but it can be scheduled in periods of reduced load or reduced electricity costs. In order to schedule the recharging process, the charging station has to communicate with the SPM. Furthermore, the possibility will be explored to use the vehicle batteries to supply energy to the grid during periods of peak demand.

4.8. The smart metering system

A Smart Metering System (SMS) will be installed in the SPM in order to acquire in real time electrical/thermal data through an interface permitting the communication with the central control system.

4.9. The SPM technologies: models, tools and research challenges

The research challenges on the technologies previously described, and in general on the technologies related to smart grids, could be faced from two different points of view: (1) development of innovative technologies/systems or (2) modeling and testing of existing technologies/systems. Alonso et al. [22] say that, in order to increase renewable energy penetration but without disregarding security and reliability aspects, distribution power networks need to evolve to smart grids, in which distributed intelligence, communication technologies and automated control systems work as the driving factors. To this end, the authors propose a generalized optimization model to determine the optimal location of distributed generators to offer reactive power capability.

Bliek et al. [23] show that micro cogeneration and hybrid heat pump systems and gas infrastructures play an important role in smart grids, balancing networks when intermittent renewable energy sources are used on a large scale. The authors report the description of a demonstration project in the city of Groningen in the Netherlands, where 25 regular households are interconnected via a local energy market and are equipped with micro cogeneration units, hybrid heat pumps, photovoltaic, smart appliances, electric vehicles, wind farm and electrical storage. This last component is fundamental for the integration of renewable energy in distribution grids. The electrical storage allows to balance energy production and load demand and an appropriate

storage management system is essential for the effective utilization of storage units in the grid as reported by Guasch and Silvestre [24].

Nowadays, many software applications are available on the market to model energy systems using different approaches: some commercial software products permit to make detailed analyses of the behavior of mechanical and electrical components in steady state and transient conditions, while other programs simulate each component as a black box. In accordance with Chicco and Mancarella [25], each component of a multi-generation system can be characterized by means of its black-box characteristics, which give the energy input–output interactions with the other plant components, described through conventional energy efficiency indicators without going into further details by complicated formulations. It is also possible to aggregate various equipments into major subsystems in order to represent the behavior of the analyzed generation system by considering a limited number of physical variables.

In some cases, the user can implement the equations that constitute the mathematical model of the energy system, while in other cases it is only possible to choose defined objects, each one schematically representing a certain type of energy conversion system or equipment (such as a gas turbine, a steam turbine, etc.). Furthermore, there are software applications that give also the possibility to evaluate environmental and economical aspects connected with the use of energy systems; this is more and more a crucial issue since, nowadays, it is essential to analyze energy system taking into account problems related to the environment (carbon dioxide emissions, pollutants, etc.) and the profitability of investments. However, as stated by Healy in [26], smart energy use can only be effective in a market and regulatory environment favorable to the effective exercise of consumer sovereignty, which represents a change of view in comparison with the historically conditioned supply-side oriented strategy.

About the evaluation of economical issues for smart grids, Celik et al. in [27] describe a flexible tool which has been developed in order to optimize the operation of a photovoltaic system combined with storage units, considering present and future market prices of the electricity; the proposed tool is based on hybrid (system dynamics model and agent-based model) simulation and meta-heuristic optimization.

As previously mentioned, cogeneration systems represent one of the best technologies to be installed in smart grids. In this sector, gas turbines and internal reciprocating engines are mature, reliable and flexible technologies. As assessed by Abdi et al. in [28] the transient behavior of a micro gas turbine system can be represented by detailed nonlinear dynamics modeling; in particular, the authors propose an optimization model to find the best controller parameters in order to have the most suitable specification for fuel consumption. Then, it is also important to evaluate the effects of the variability of ambient conditions on the gas turbine performance, as suggested by Bracco et al. [29]. Guo and Guo [30] have developed a modularized model, creating an electro-mechanic simulator of a single-shaft micro-turbine generation system including the micro-turbine engine, the permanent magnetic synchronous generator, the rectifier and the inverter; the control system is made up of speed control, temperature control and acceleration control. Furthermore, Guo and Guo [30] propose a new control strategy to regulate the gas turbine power output. Coates et al. in [31] describe a generic optimal online linear programming optimizer that has been developed for operating a CHP system; the optimizer, which can be embedded within the CHP control system, is able to minimize daily operation costs of such a system, taking into account technical and operational constraints.

Furthermore, it is important also to cite the use of cogeneration technologies combined with various thermally fed systems

such as absorption or engine-driven chillers: this is the so called trigeneration, well described by Chicco and Mancarella [25]. In a lot of cases these plants, namely combined heat, cooling and power systems, as reported by Bruno et al. [32], consist of a micro gas turbine in which the exhaust gas at the turbine exit is used to heat a fluid to produce cooling with an air cooled absorption chiller and hot water for heating and the water domestic circuit. In particular, Bruno et al. [33] tested a trigeneration system in different operating conditions by varying the power output of the micro gas turbine, the ambient temperature for the absorption unit, the chilled water outlet temperature and the thermal oil inlet temperature. The electric behavior of the micro-turbine has been simulated by means of a model able to reproduce the system behavior in off-design and transient conditions. Gordon and Choon [34] propose a general thermodynamic model for cooling devices and show how the chiller coefficient of performance depends on cooling rate and key system variables.

Gutierrez-Urueta et al. [35] analyze theoretically the thermodynamic performance of a trigeneration system formed by a micro-turbine and a double-effect water/LiBr absorption chiller. Chau et al. [36] report a detailed description of different types of indirect-fire absorption chillers: these systems are most of times double-effect, while the higher-performance triple-effect technology is being lately introduced in the market. The heat, usually discarded by means of a cooling tower, could be recovered and, often, the machine is reversible and could be used also under heating mode as a heat pump. The high complexity of these systems calls for powerful analysis tools, which model the components behavior as a succession of steady state conditions, for instance using a discrete step for the time scale not lower than 1 h, in order to neglect the faster effects on the dynamics of the equipment operation. Chau et al. [36] also say that in some cases the models are based on a synthetic black-box approach, in which the relevant variables are energies, conversion factors, equipment efficiencies, and the descriptors of the interconnections among the system units.

As far as research on renewable resources applied to smart or microgrids is concerned, it should be noticed that such kind of generation units are characterized by undoubted advantages, above all from the environmental point of view, but they also complicate the planning and operation of microgrids due to their intermittent production and their need for power inverters. As analyzed by Berry et al. [1], the existing microgrid installations are characterized by massive use of wind energy. As reported by Marinescu and Serban [37], among renewable energy sources, wind power recorded the fastest growth in the last decade. While large wind turbines have reached the technological maturity, small-scale wind energy conversion systems have to be further optimized in order to provide a reliable service in smart grids. At this purpose, Marinescu et al. [37] propose an innovative sensorless control system for small variable-speed, fixed-pitch wind turbines operating at partial-load and full-load modes, from cut-in to cut-out wind speeds.

Nowadays, the market offers different wind turbines, mainly classified in horizontal or vertical axis wind mills. For both basic configurations, different technological solutions have been investigated, depending on the installation site conditions. From this point of view, Proven and Sharpe [38] propose the Crossflex solution, that is a radical new development of a Darrieus turbine: as well as having a technically innovative flexible blade system, it is also characterized by a lightweight cowling system that provides both augmented airflow and improved visual integration into new and existing buildings. Ayan and Saglam [39] investigate the application of wind turbines in buildings too, and analyze the wind aerodynamics and wind flows over the buildings basing on meteorological data and building characteristics.

Environmental Decision Support Systems (EDSSs) can be used for the optimal choice of location, technologies and size in the wind energy sector. For example, Ouammi et al. in [40] refer to an EDSS for the sustainable design of wind power plants both in terms of the site selection over a regional territory and of the optimal technology to be installed. The authors underline the importance to analyze the wind speed statistical distribution through accurate monitoring campaigns and to choose wind turbines characterized by high efficiency and a reliable control system. As a consequence, to model a wind system installed in a smart grid, it is necessary to know: the efficiency and the geometrical dimensions of the machine (diameter, height, etc.), the environmental data (ambient temperature and pressure, humidity), the wind characteristics (obtained by monitoring campaigns); furthermore, it is essential to have the wind turbine characteristic map that plots the power output as a function of the wind speed. Sahin [41] describes wind energy formulation and measurements, turbine technology, power control, stall and pitch control.

As regards the solar energy, El Chaar et al. [42] give a full review on the development of photovoltaic technology, focusing on the four major current types of PV: crystalline, thin film, compound and nanotechnology. They underline the fact that multi-crystalline silicon modules are more attractive in terms of purchasing cost even though the cell efficiency is lower than that of mono-crystalline cells. Nevertheless, it is important to say that, as reported by Diniz et al. [43], the actual decreasing prices of photovoltaic systems have been driven by solar cell efficiency and manufacturing improvements and economies of scale. Goic et al. [44] report a review of major solar photovoltaic technologies and the different applications of solar photovoltaic systems, such as building integrated systems, desalination plants, and solar home systems. As reported by Goic et al. [44] the commercially available multi-crystalline silicon solar cells have an efficiency around 14–19%. As assessed by Gottschalg [45] the performance of photovoltaic modules is affected by the operating temperature. The authors report a brief discussion on the effect of the operating temperature on a commercial silicon-based solar module and list some correlations that permit to estimate the module power output as a function of the operating temperature. Venayagamoorthy and Welch [46] propose an optimal energy control scheme for a grid independent photovoltaic (PV) solar system consisting of a PV array, battery energy storage, and time varying loads. In order to simulate a photovoltaic solar system it is necessary, first of all, to know the technical performance curves of the components, which show the effect of the ambient temperature and the solar insolation on the current and voltage values, in order to correctly estimate the power output. Several commercial simulation tools are available on the market to easily model a photovoltaic system and to calculate the main operating parameters which describe its performance, taking into account important exogenous effects such as shading, adverse weather conditions or inaccurate maintenance interventions.

Connected with the use of solar energy, many installations in smart grids are relative to solar-powered Stirling engines. As well described by Kongtragool and Wongwises in [47], Stirling engines are mechanical devices working theoretically on the Stirling cycle, in which compressible fluids, such as air, hydrogen, helium, or other gases are used as working fluids. The Stirling engine is an external combustion machine, in which the heat supplied can derive from most sources, including combustion of any combustible material, field waste, rice husk or biomass, methane and solar energy. In particular, direct solar-powered Stirling engines are more and more adopted in countries where solar energy is available in unlimited quantity. Kongtragool and Wongwises [47] report an interesting review on solar-powered Stirling engines.

Another study on this subject is reported by Srikam and Sripakagorn [48]: the authors describe a prototype of moderate temperature Stirling engine used as prime mover for concentrating solar power technology; the proposed solution is characterized by low cost materials and simplified mechanical design. Moreno [49] focuses the attention on the innovation in concentrated solar power technologies over the last decade, regarding reflector and collector design and materials.

5. The SPM electrical system

The goal of the present section is that of describing the SPM electrical system and of reporting models, tools and research challenges to study and simulate smart grids electrical systems.

5.1. The SPM electrical network

The University of Genoa Smart Polygeneration Microgrid (SPM) located in the city of Savona includes an electrical system characterized by one MV/LV transformer substation made up of three transformers: two supply the electrical load distributed in the Savona University Campus, and one connects the SPM to the external grid. The three phase low voltage (400 V line to line) distribution system is characterized by a ring network separated from the existing electrical network of the Campus in order to minimize the problems related to interferences due to research tests. The length of the network is about 500 m and it is composed of underground cables of type FG7OR $3 \times 1 \times 185 \text{ mm}^2 + 1 \times 95 \text{ mm}^2$. The ring structure has been chosen to expand the SPM without an increase in size of the main electric switchboard located in the electrical substation.

As visible in Fig. 3, the distribution system is made up of five electric switchboards. The first one, called +QGEN, is the general electrical switchgear that interfaces the SPM with the public distribution. It is located in the transformer substation and it allows for the configuration of the operating mode: grid-connected or island mode, resynchronization, ring or radial grid configuration. The other switchboards are located in the Campus area, as described in Fig. 3. Everything is arranged to connect three main generators and three main loads of different size and furthermore the switchboards have been designed to allow for further expansion. In particular, the electrical box +Q01 connects three generators (photovoltaic system and two concentrator solar powers) and one main load (auxiliary services of the control room). The electric switchboard +Q02 connects the electrical storage system and one electrical vehicle charging station, while the electrical box +Q03 connects some energy laboratories and one micro wind turbine. Finally, the electrical box +Q04 connects the micro gas turbine, one micro wind turbine and the remaining electrical vehicles charging station.

As far as the communication system is concerned, all the devices of the microgrid test-bed are equipped with interfaces, which are either compatible with the new protocol IEC 61850 or connected via appropriate protocol translators. Therefore, it is possible to perform test on such protocol in a low voltage distribution grid with high penetration of renewable sources. This research topic is presently of great interest in the international scientific community, since it represents a novel application of the standard IEC 61850, up to now mainly employed for communication management in high and medium voltage substations.

5.2. Models, tools and research challenges

In this paragraph, the challenges that will be faced thanks to the use of the SPM are outlined in the context of current research activity in the field.



The research activities carried out on the SPM microgrid will primarily focus on the DER management. The integration of DER, renewable ones in the first place, leads to a number of issues. First, random variability of solar radiation or wind speed in the hours to day time scale, makes it very difficult or impossible to follow a day-ahead production schedule; thus, a large penetration of renewable sources could lead to increased power system operational costs, due, for instance, to the augmented need of spinning reserve: as an example, in [51] the problem of costs

The microgrid concept, where loads, sources (both renewable and dispatchable) and storage systems coexist and are operated under a common management, is a possible solution for these issues; in particular, in the SPM they will be faced according to the following lines. Advanced methodologies based on both short term weather forecasting and electric storage will be developed

and tested for their ability to allow following a day ahead production schedule [56,57], within a given tolerance band. In addition, the presence of an electric vehicle recharge station will give the opportunity to test the contribution electric vehicles can offer performing as additional storage units [58].

As far as the voltage profile control is concerned, the advantages offered by approaches based on global voltage and power flux management (see, e.g., [59]) will be assessed: these approaches are aimed at maintaining the voltage values of all the grid nodes in the prescribed bounds by means of a coordinated action on the sources voltage/reactive power references. To cope with the rapid variations of the injected power characterizing the renewable sources, both short (super capacitors) and medium (NaNi batteries) term electric storage will be exploited [60,61], coordinating them with the programmable source (micro-turbine). Special attention will be paid to dynamic limit on charge/discharge rate (i.e. power absorbed or delivered) imposed to the battery energy storage systems by their PCS (power conversion systems [62]).

In order to achieve the economic feasibility of a smart microgrid, it is fundamental to explore all the remunerated ancillary services (i.e. other than to provide active power) this infrastructure can deliver to the DSO grid [63,64]. In particular, the possibility to perform voltage support by delivering reactive power will be investigated. To this end, when selecting the converters connecting, e.g., the PV system, special attention has been paid to its characteristics in terms of reactive power generation and regulation capabilities.

Furthermore, this set of functions requires a telecommunication infrastructure able to guarantee the interchange of information between the management system and the smart controllers, installed on the field and collecting data, acquiring measures and sending commands to field actuators and devices: to this end, as previously stated, a communication backbone based on Ethernet and the IEC 61850 protocol will be used. Applications of this protocol to the microgrid environment are relatively new [65], so the SPM will represent a test-bed to assess its performance and possible limitations (for instance, when dealing with non-conventional equipments such as the installed Stirling CSP system).

Beside renewable integration, also the possibility to operate the microgrid in islanding mode to increase power quality and supply reliability will be investigated.

Electromechanical simulations will be performed in order to assess the microgrid behavior in response to perturbations and stability analyses will be carried out considering various operating condition. From this point of view, a microgrid significantly differs under several aspects from a conventional active portion of a power network (typically, at MV or HV level): a microgrid with a relatively small rated power can be subjected to comparatively severe and frequent transients (due to transition to islanding mode, the aforementioned rapid variations of injected power from renewable sources, etc.), thus leading to the need of advanced control methodologies such as sliding mode [66]. Similar considerations hold for small signal stability: as pointed out in by Zeng et al. [67], microgrids are characterized by a wide span of operating conditions (depending on generation and load variability, connection status with the main grid, etc.), so classical approaches to small signal stability could not be suitable for this application. Two of the most popular power system simulation environments (NEPLAN [68] and DIgSILENT [69]) have been selected to perform this task and the advanced measurement equipments, together with the capabilities of the communication infrastructure, will allow closely comparing the theoretical analyses on control methods and stability criteria with the experimental results obtained after their implementation. Furthermore, new dynamic models will have to be synthesized for those

components (such as Stirling CSP – concentrating solar power and battery storage systems together with their PCS) currently not included in the library of commercial simulation programs: for this purpose, the flexibility of the two aforementioned environments (NEPLAN and DIgSILENT) in defining custom models will be fully exploited.

Simulations will also offer the possibility to address the issue of protection coordination: as highlighted, for instance [70], to find a protection strategy which is effective both in grid connected and islanding operation, taking also into account the small contribution of the converters to the fault current, is a major challenge in smart grids.

The experience gained by operating the SPM will help evaluating the reliability of the microgrid components and of the overall system, thus providing experimental data for reliability analyses [71,72].

6. The SPM thermal system

In the present section the SPM thermal system is briefly described and models, tools and research challenges to study and simulate district heating systems are reported.

6.1. Synthetic description of the thermal system

In Fig. 4 the schematic map of the SPM thermal network is depicted. The SPM new technologies and the thermal devices already present in the Campus are indicated, in order to show the configuration of the whole thermal system which will constitute the “Campus District Heating Network”.

The core of the Campus thermal system is located in the area of the Thermal Power Station (also indicated in Fig. 2). The two traditional boilers (each characterized by a thermal power of about 400 kW_{th}) and the two cogeneration gas turbines (C30 and C65 models) provide the thermal energy to the water circulating in the district heating network which serves almost all buildings (Locatelli, Branca, Marchi, Lagorio, Delfino), the canteen, the library, the changing room and the residence halls located near the canteen. On the contrary, the Aula Magna and the classrooms located near the hangars (in the northern zone of the Campus) are heated by a dedicated boiler, whereas the residence halls located near the library are heated by a heat pump system. The heating system is averagely operative five months a year, from the beginning of November to the first days of April. The three hangars and the other buildings, used as energy labs, are not heated.

Regarding the conditioning system, it is important to say that, during the summer, some buildings (Locatelli, Branca, Marchi, Lagorio) use dedicated and centralized heat pump refrigeration units located on the roofs, whereas in the Delfino Building single conditioning units (one for each office) are adopted.

During hot months, the thermal energy extracted from the exhaust gas discharged by the C65 gas turbine is used by the two absorption chillers to produce cold water (at a temperature of about 7 °C) for the library refrigeration plant; the cold water is stored in a tank having a capacity of 3000 l, located near the chillers.

The two solar-powered Stirling engines are positioned near the library and the student residence halls. In particular, the thermal energy extracted by the two engines is transferred to the domestic hot water provided to the residence building; for this purpose, the installation of a heated water store, having a capacity of 1000 l, is necessary. The system will integrate with the thermal solar plant already installed on the roof of the building.

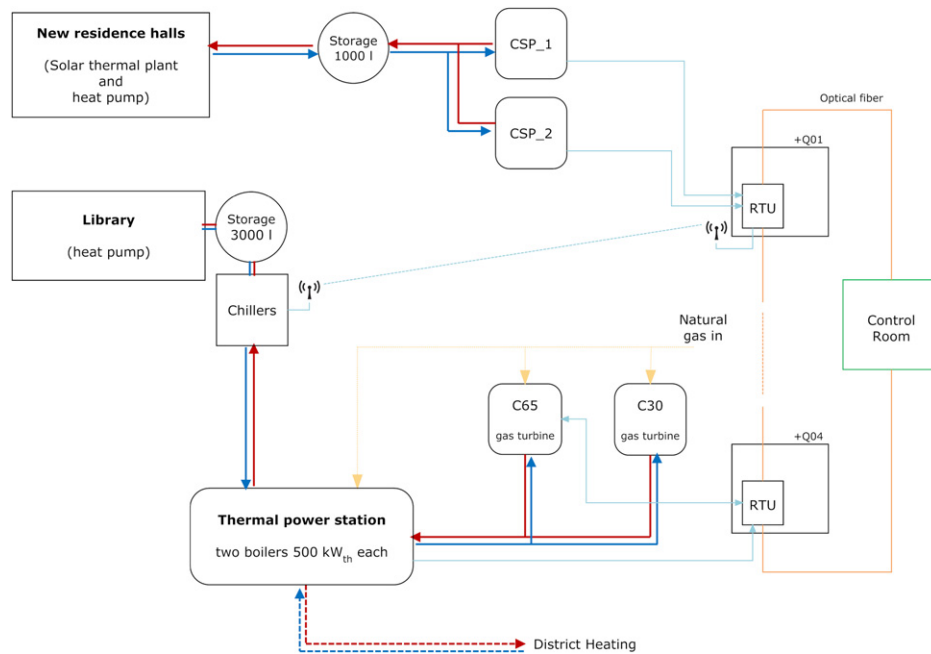


Fig. 4. The Savona University Campus district heating network.

6.2. Models, tools and research challenges

In literature, apart from the research challenges related to the technologies present in a thermal system, there are different works that deal with the modeling and the management of district heating systems and of thermal systems in general.

As reported by Rezaie and Rosen [73] and Colella and Verda [74], district heating systems are composed by one or more thermal plants, and a distribution network of insulated pipes where hot water, superheated water or steam flow, delivering heat to the users through heat exchangers. Rezaie and Rosen [73] present a review of definitions, classifications and applications of district cooling and heating systems, and describe the key elements which characterize a district energy system. The analysis takes into account technical, environmental and economical aspects and shows that using waste heat from electricity production plants increases efficiency and avoids emissions, helping to enhance the quality of the environment; in particular, Rezaie and Rosen [73] focus the attention on combined heat and power systems, and report a detailed analysis of advantages and disadvantages of “district energy”. As assessed by Abonyi and Abonyiet [75], who propose a multilevel optimization model for a district heating network, the main advantages of such a system are due to the increase in the energy conversion efficiency (for example by means of CHP plants) and to the reduction of the environmental impact (exploiting renewable sources where available or using waste heat).

The advantages of district heating and cooling systems in terms of energy efficiency are also described by Bales et al. [76], and Isayama et al. [77], where the authors refer to systems composed of cogeneration units and absorption chillers.

Persson and Werner [78] examine the future competitiveness of district heating systems, taking into account future trends of distribution capital costs as a function of various city characteristics, city sizes, and heat demands; the authors also believe that district heating is expected to remain competitive in high heat density city districts and large city areas, whereas in low heat density areas local heating alternatives are expected to dominate.

Benonysson et al. [79] describe a mathematical model, based on the “node method”, which incorporates the consumers, the district

heating network and the production plants; the objective function is to satisfy the consumers’ heat demand in the cheapest possible way, that is minimizing operational costs, but also considering environmental issues. The authors also outline that the planning of a new district heating system requires the detailed analysis of the heat demands and the probable future development of these last must be analyzed too. The importance of having reliable experimental data is also underlined by Bohm et al. [80]: they use time dependent consumer data from the Naestved district heating system in order to investigate the ability of modeling tools to represent the temperature profile distortion throughout an entire heating system network. In this field, Jie et al. [81] propose a mathematical model to study the dynamic characteristics of a district heating network, focusing on the calculation of the “lag time” and of the “relative attenuation degree”.

Genon et al. [82] pay the attention on district heating cogeneration systems which are analyzed from an energetic and environmental point of view, focusing on nitrous oxides emissions from natural gas fueled engines and remarking that pollutants deposition is strictly connected to the morphology of the territory and to the stack height. Favrat et al. [83] consider environmental issues too: in particular, they suggest that systems integrating heat pumps and cogeneration units offer a significant potential for greenhouse gas emissions reduction; they describe a multi-objective and multi-modal evolutionary algorithm implemented to facilitate the design and planning of a district heating network based on a combination of centralized and decentralized heat pumps combined with on-site cogeneration units. Colella and Verda [74] underline also the importance of using storage tanks to increase the annual operating hours of CHP systems and, as consequence, to save energy.

Finally, it is important to cite the study proposed by Gokcen et al. [84], that present the design of a geothermal district heating system with heat pumps for a University Campus, comparing it with a fossil fuel district heating system.

7. The SPM control system

The systems and the technologies described in the previous sections are integrated in the Savona Campus SPM through an

overall management system (SCADA) that is responsible of the various operations, namely regulation, optimization and monitoring (Markovic et al. [85] Bazmi and Zahedi [86] and Banos et al. [87]).

In this section, firstly the overall SPM management system is described. Then, the integration of control and optimization approaches is discussed. Finally, a review on research challenges related to methods and models useful for optimal planning and control purposes is reported.

7.1. The SPM control system: architecture

The SPM is governed by a monitoring, supervision and control system able to module the power generation as a function of connected users, of the desired generation policies, and of the exchanges with the external Distribution System Operator.

The overall management system is structured in a way to create an open system, modular, flexible and designed to allow future SPM developments (new generating units, new thermal and electrical loads). For this reason, it has been decided to install a control network that uses both communication protocols that are consolidated (Modbus, RS485, etc.) and the protocol IEC 61850 that, in future years, should become a reference standard for communications and control architectures in smart grids [65].

The overall management system is reported in Fig. 5. It is made by the following three subsystems:

- Interfaces with SPM components: devices that directly interact with the electrical network (RTUs-Remote Terminal Units) by measuring of relevant parameters (i.e., current, voltage, temperature, etc.) and through control actions. The RTUs directly interact with the centralized control system. RTUs are placed inside the electric distribution switchgears. Each RTU is connected to a specific set of generating units (PV, CSP, electrical storage, etc.).
- Data communication network: it constitutes the communication system over which there is the bidirectional data exchange between the control room and the devices in situ. Following the standard IEC 61850, it is an Ethernet ring structured network designed using connections in optical fiber among communication nodes located in each distribution switchgear.
- A centralized management system: the system intelligence that allows the supervision and control necessary to guarantee an effective management of the network with the aim of optimizing generation on the basis of the information coming from the RTUs on the field. The “system intelligence” will correlate these data with additional information like

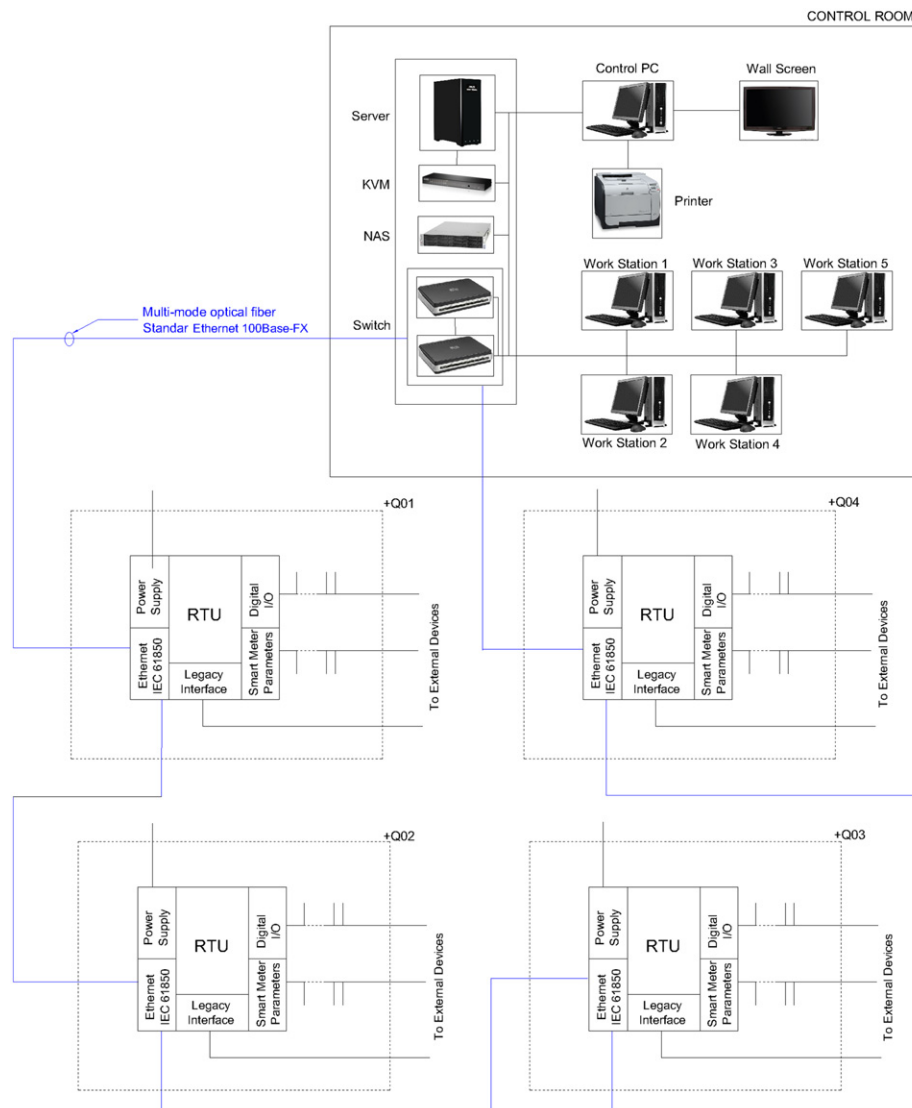


Fig. 5. The overall SPM management system.

meteorological forecasting, energy costs, etc., for the definition of personalized policies (for example based on optimization algorithms).

The overall management system will be installed in a control room equipped with a server, an UPS module and a conditioning system. In such room, it will be possible to monitor the overall system state and that one of each single SPM component. Specifically, it will be possible to acquire data from the single user and from the single generation unit, to give commands to users and generators (also establishing priority levels). A NAS (Network Access Storage) will register the time history of available data. The software for the overall system management guarantees the SPM operations, monitoring and alarms management, through the connections with the RTUs and local control panels of generators on the field. Moreover, it allows adding new components, models and tools useful for the optimization and control. The software is characterized by a Graphical User Interface that immediately shows a schematic representation of the smart grid.

7.2. Models, tools and research challenges

The research challenges are essentially related to the possible models and methods for optimizing the overall microgrid planning and control, also analyzing environmental and technical benefits provided by the deployment of smart power grids. On this specific subject, Delfino et al. [88] present a procedure to quantify the CO₂ emission reduction, the decrease in energy losses and the increase in renewable energy generation deriving from the transmission and distribution infrastructures renewal.

Planning problems can be typically referred to medium-long term decision problems in which no information in real time is needed (see for example, Frombo et al. [89,90], Minciardi et al. [91], Minciardi and Robba [92]). They can be formulated either on the single production unit and/or component, or on the overall mix of possible generation technologies. For example, in the case of the SPM, a planning problem could be stated to determine the more suitable technologies to adopt, their number and optimal location and the constraints could be relative to economic, environmental and technical aspects.

On the other hand, control problems are related to short term decisions in which real time information can be used. In the case of the SPM, they can be referred to the determination of suitable rules for storage management and generation scheduling.

For each class of decision model, the following tasks have to be taken into account and integrated: simulation, optimization, and data storage [89,90,93]. It is possible to develop physically-based or black-box simulation models in order to describe the behavior of the various sub-systems that constitute the smart grid. These models can be employed to analyze the electrical network and its power flows, the thermal system, the resources availability, the environmental impact, and the operating costs.

The Savona University Campus SPM, as previously described, includes different sub-systems and technologies that have to be modeled through specific simulation tools. The challenge is how to integrate the different models and how to make them interact with the optimization algorithms. Two possible approaches can be applied

- To define simplified models to be embedded in the optimization algorithms and then validate optimal results through a simulation tool.
- To define new architectures for simulation/optimization purposes.

Simulation tools in microgrids often need as input the forecasting of renewable resources availability and the estimation of

electrical and thermal demand in order to implement policies for real time optimal control.

On this particular topic, Angelis-Dimakakis et al. [94] review methods and tools to estimate the potential of different renewable sources (i.e., solar, wind, wave, biomass and geothermal). Foley et al. [95] present a survey on wind power forecasting, with specific reference to numerical vector wind field prediction from global to local scales. Erdem and Shi [96] describe four approaches based on Auto Regressive Moving Average (ARMA) algorithms to forecast wind main physical parameters. Amjady et al. [97] propose and validate a wind power forecasting strategy composed of a feature selection component and a forecasting engine. The feature selection component applies an irrelevancy filter and a redundancy filter to the set of candidate inputs. The forecasting engine includes a new enhanced particle swarm optimization component and a hybrid neural network. Bouzguou and Benoudjit [98] present an approach combining predictive power outputs derived from multiple models in order to improve the performance of the prediction process. As regards solar energy, Tanaka et al. [99] forecast the solar irradiance using fuzzy logic within an optimization model for the optimal operation of a smart grid to minimize the power flow fluctuation at the grid interconnection point. Kemmoku et al. [100] propose, instead, a multi-stage neural network, while Ramachandran and Pearsall [101] discuss a synthetic algorithm to generate a set of data concerning with solar irradiance for different locations. The use of the Markov Transition Matrix method to generate hourly global horizontal radiation series is described and compared with measured data.

As far as the energy demand prediction is concerned, Suganthi and Samuel [102] review different forecasting models. They recall traditional methods (such as time series, regression, econometric, ARIMA, as well as soft computing techniques such as fuzzy logic, genetic algorithms, and neural networks) that have been extensively used for Demand Side Management (DSM). They assess that Support Vector Regression, Ant Colony and Particle Swarm Optimization are efficient techniques to be adopted for energy demand forecasting. Dilaver and Hunt [103] investigate the relationship between Turkish residential electricity consumption, household total final consumption expenditure and residential electricity prices by applying the structural time series model to annual data.

With specific focus on energy tariffs, Shafie-Khah et al. [104] propose a novel hybrid method to forecast day ahead electricity prices. This hybrid method is based on wavelet transform, Auto-Regressive Integrated Moving Average (ARIMA) models and Radial Basis Function Neural Networks. Areekul et al. [105] provide a hybrid methodology that combines both ARIMA and artificial neural network (ANN) models for predicting short-term electricity prices.

Coming back now to planning decision problems, it should be highlighted that they can be very complex because it is necessary to deal with non-linear multiple objectives problems, referred to one or more decision makers (stakeholders).

Indeed, the choice of the best technologies to install in a smart grid depends on technical, environmental, economical and social aspects, taking also into account the physical constraints of the system: as reported by Uston et al. [106], a microgrid can be a DC, AC or even a high frequency AC grid, it can be a single or a three phase system or it may be connected to low voltage or medium power distribution networks.

In literature, there are several papers facing planning problems with specific application to the field of renewable energies, through the application of optimization techniques. Ouammi et al. [40] propose an Environmental Decision Support System (EDSS) for the sustainable design of wind power plants both in

terms of the site selection over a regional territory and of the optimal technology to be installed. Frombo et al. [89,90] describe a GIS-based EDSS to define planning and management strategies for the optimal logistics for energy production from woody biomass, such as forest biomass, agricultural scraps and industrial and urban untreated wood residues. Dagdougui et al. [107] present a two objective constrained optimization model to evaluate the performance of a thermal solar system. Alarcon-Rodriguez et al. [108] provide a review of the state-of-the-art in multi-objective DER (Distributed Energy Resources) planning, and discuss in detail the challenges, trends and latest developments in this field.

EDSSs can be developed including such multi-objective optimization models for the mix of energy resources. Examples related to design and planning decision problems can already be found in the literature but more flexible and integrated tools are still necessary [94].

In the specific context of microgrids, Chen et al. [109] present a methodology for the optimal allocation and economic analysis of an energy storage system (ESS) in microgrids. To optimize the operation strategies and system size, dynamic models of ESS are discussed. Mohammadi et al. [110] present an optimized design of a microgrid in distribution systems with multiple distributed generation (DG) units (among which PV, wind turbines and batteries). An objective function with the purpose of maximizing net present value (using PSO—Particle Swarm Optimization as a solution method) is presented. Marnay et al. [111] propose an optimization approach to incorporate electrical and thermal storage options in the Berkeley Lab's Distributed Energy Resources Customer Adoption Model (DER-CAM).

Chen and Gooi [112] recall that Unit Commitment (UC) and optimal power flow (OPF) are two of the key functions in the operation of the microgrid, particularly in the network management of distribution systems. The UC function is responsible for the economic optimization of the power system, and the OPF function is responsible for the security optimization of the network. They design a multi-objective optimization algorithm to solve at the same time cost minimization as well as energy losses minimization for the microgrid. This will predict the injected active and reactive powers, bus voltages and angles, optimal transformer tap ratios, and phase shifter angles. They consider UC and OPF at the same time to obtain a multi-objective optimization for both planning and real-time operation, through the use of a new technique called as the “jump and shift” method.

Another interesting research line in the context of smart grids is related to real time optimal control problems (Dagdougui et al. [113], Xia et al. [114]) that usually are aimed at the best management of intermittent renewable sources.

Chen et al. [115] present a Smart Energy Management System (SEMS) to optimize the operation of the whole network. The SEMS consists of a power forecasting module, an energy storage system (ESS) management module and an optimization module. The characteristics of the PV unit output in different weather conditions are studied and then a 1-day-ahead power forecasting module is described. Smart management of ESS, economic load dispatch and operation optimization of DG are simplified into a single-objective optimization problem. Dagdougui et al. [113] propose an optimal control algorithm for a hybrid macrosystem integrating subsystems such as an electrolyzer, an hydroelectric plant, pumping stations, wind turbines, fuel cells. On the basis of this dynamic model, a constrained optimization problem is formulated to satisfy a variable hourly electric energy demand. Katiraei and Iravani [116] highlight some electrical issues that could be considered in a decision model for microgrid operation. Specifically, they address real and reactive power management strategies of electronically interfaced DG units in the context of a

multiple-DG microgrid system. Hernandez-Aramburo et al. [117] present an optimization problem based on a cost function to reduce the fuel consumption rate of the system while constraining it to fulfill the local energy demand (both electrical and thermal) and to provide a certain minimum reserve power. The optimization problem includes a variety of energy sources that are likely to be found in a microgrid: gas fired reciprocating engines, a combined heat and power micro-turbine, PV and wind generators.

Tsikalakis et al. [118] describe the operation of a central controller for microgrids. In particular, the hierarchical control system architecture is based on three levels. The controller aims to optimize the operation of the microgrid during interconnected operation, i.e., maximize its value by optimizing the production of the local DGs and power exchanges with the main distribution grid. Two market policies are assumed including demand-side bidding options for controllable loads.

Hooshmand et al. (2012) [119] present a stochastic model predictive control method for managing a microgrid that takes into account the stochastic disturbance inputs and various constraints imposed by the distribution lines and battery level of charge.

Dimeas and Hatziargyriou [120] present the operation of a multiagent system for the control of a microgrid. The main idea of their algorithm is that every DER or controllable load decides what is best for it, taking into account the overall benefit through a specific algorithm.

Logenthiran et al. [121] propose a multiagent system for real-time control and management of a microgrid using real-time digital simulation under a set of suitable operational conditions. The proposed operational strategy is mainly focused on generation scheduling and demand side management. Tan et al. [122] present a centralized control system that coordinates parallel operations of different distributed generation inverters within a microgrid. A new Model Predictive Control algorithm is adopted; it allows faster computational time for large power systems by optimizing the steady-state and the transient control problems separately.

Abdel-Rady et al. [123] introduce a robust hierarchical control system of distributed generation converters for microgrid operation and seamless transfer between grid-connected and isolated mode. Comparative experimental results are discussed to validate the effectiveness of the proposed control scheme and to highlight the stability and the reliability of microgrid operation. Dou et al. [124] present a novel hybrid model to explain the hybrid interactive behaviors of microgrids. On the basis of the model, a two-level hierarchical hybrid control is proposed based on the hybrid system control theory in terms of interactive adjustment between the continuous controller at the lower level and discrete management at the upper level. The upper-level discrete management strategies are responsible for guaranteeing stability and security of the overall microgrid, while constraining it to meet the load demand during significant disturbances, as well as minimizing the operating cost and reducing the emissions during normal situations. The lower-level local continuous controllers are responsible for regulating the dynamic performance of each controlled unit.

Colet-Subirachs et al. [125] focus on a simple method for controlling the active and reactive power of a utility connected microgrid operating in grid-connected mode. It is based on peer-to-peer and plug-and-play concepts and operates either in centralized or in distributed mode. Etemadi et al. [126] present a central power-management system and a decentralized, robust control strategy for autonomous mode of operation of a microgrid that includes multiple distributed energy resource units. Specifically, the strategy provides: (1) power management of the overall microgrid, (2) open-loop frequency control and synchronization and (3) a local, decentralized control for each unit.

In light of this current state of the art, the following research challenges can be identified for the real time optimal control of the Savona University Campus SPM:

- Definition of dynamic decision models (that embed simplified versions of the different subsystems described in previous subsections) for real time optimal control that take into account multiple objectives (economic, environmental, technical).
- Definition of dynamic decision models to determine production unit (generators and storage systems) commitment strategies.
- Definition and evaluation of decision problems for microgrids based on hierarchical, distributed, multilevel architectures, taking into account the different information flows.

8. Conclusions

In the present paper, the Smart Polygeneration Microgrid (SPM) test-bed facility of the University of Genoa has been thoroughly described and a detailed state of the art review on smart grid technologies and applications has been carried out.

The SPM includes photovoltaics, wind turbines, cogeneration gas turbines, concentrated solar power systems, electrical and thermal storage devices, and electrical vehicle recharging stations to satisfy different kinds of energy demands (electricity, transport, heat, cool) and is designed to be further integrated with additional emerging technologies. In addition, in the SPM, different subsystems (electrical distribution, district heating network, production and storage units, communication, control and optimization) interact, being supervised by a centralized management system; for each of the aforementioned subsystems, different research challenges have been outlined in the paper.

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